Use of adaptive beamformers in MEG source modeling

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Applications of Beamformers in MEG

- Introduction to adaptive beamformers
- Advantages and disadvantages of beamformers
- Differential vs. event-related imaging
- Examples of clinical applications

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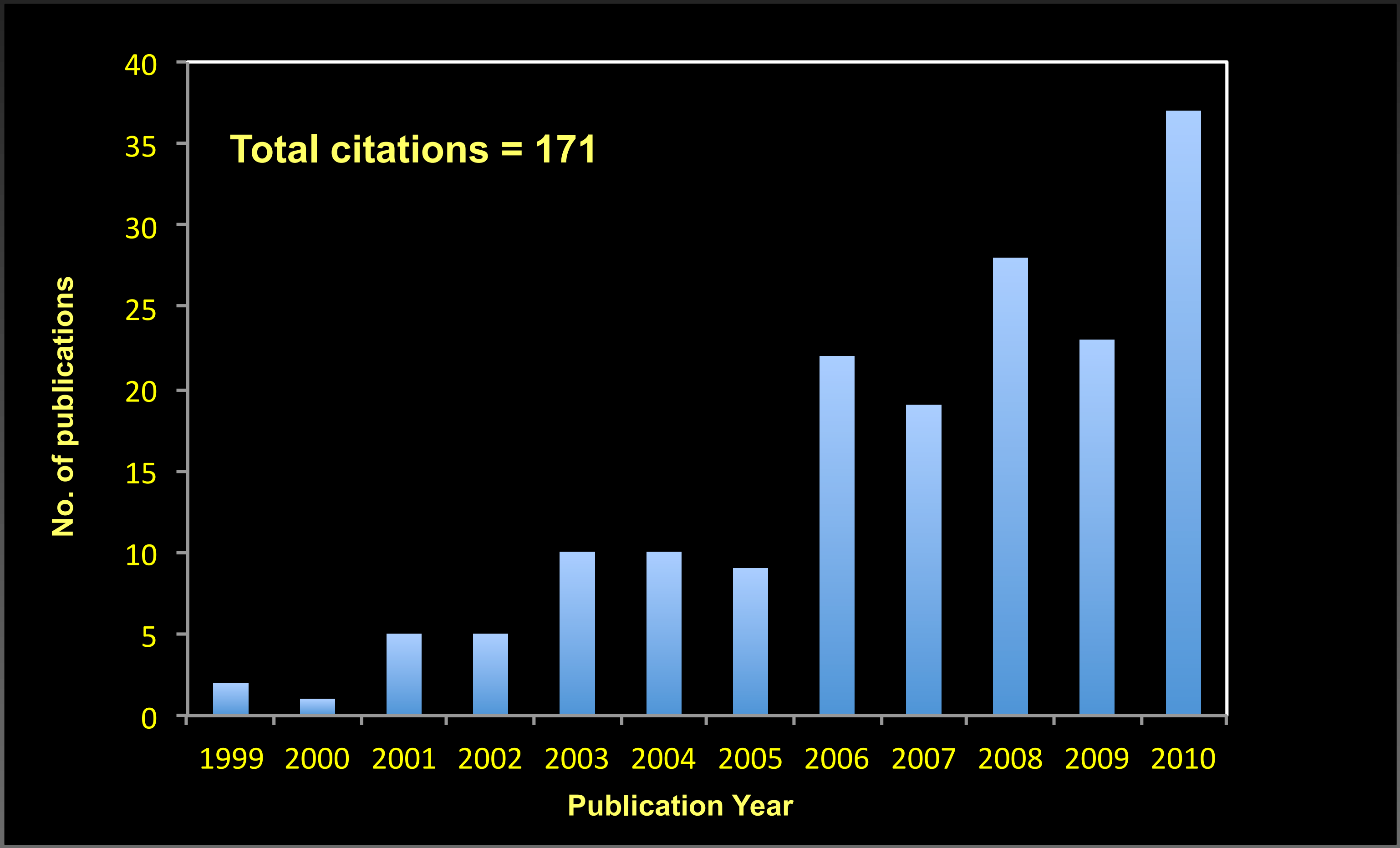
Use of adaptive beamformers in MEG/EEG

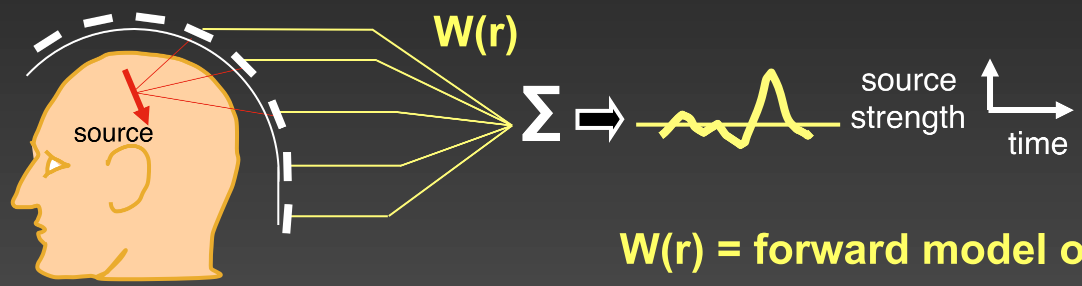
PubMed survey of studies using beamformers and EEG/MEG



Spatial filtering methods

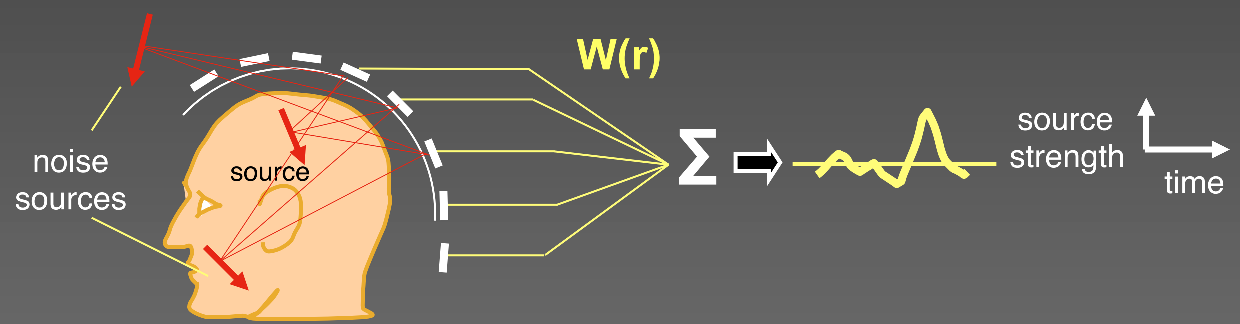
A spatial filter is the weighted output of the MEG sensor array that reflects activity at a specific brain location over time (i.e., is spatially selective for the target source)

Signal Space Projection (SSP)



W(r) = forward model of source

Beamformer



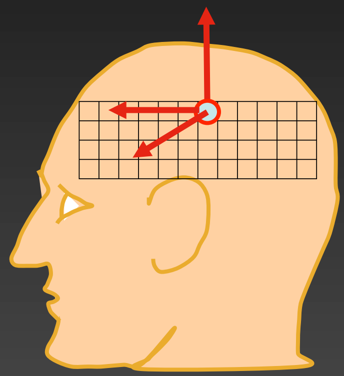
Beamformer source models – forward model

Volume based imaging

Vector beamformers

- orthogonal current sources at each voxel

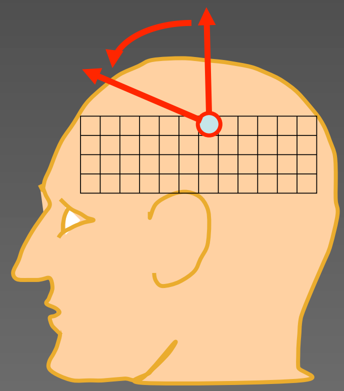
E,g.,
Linearly Constrained Minimum-Variance (LCMV) beamformer
(Van Veen et al., 1997)
Vector / eigenspace beamformers
(Sekihara et al., 2001)



Scalar beamformers

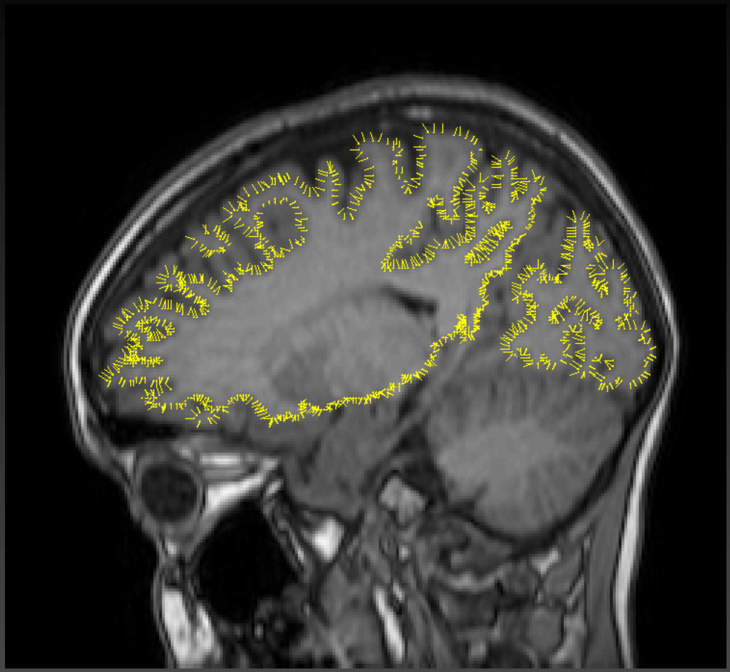
- estimate optimal current direction at each voxel

E.g.,
Synthetic Aperture Magnetometry (SAM)
(Robinson & Vrba, 1999)
Spatiotemporal (event-related) beamformer
(Sekihara et al., 2002; Robinson 2004; Cheyne et al., 2004, 2006)



Beamformer source models – forward model

Surface based imaging

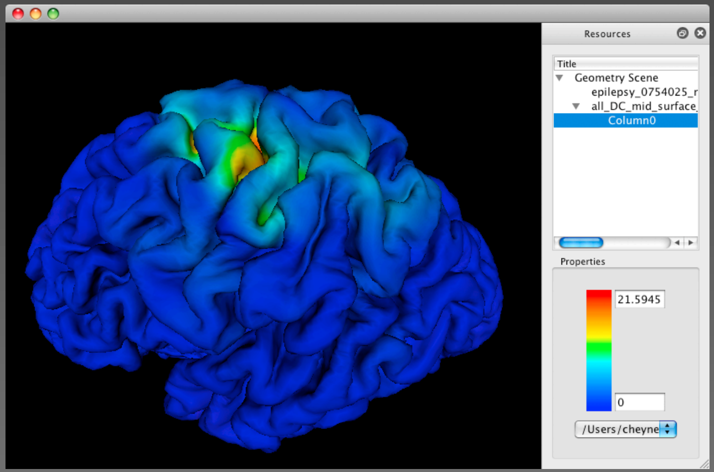


Cortically constrained beamformers

- dipole sources normal to cortical surface

Problem:

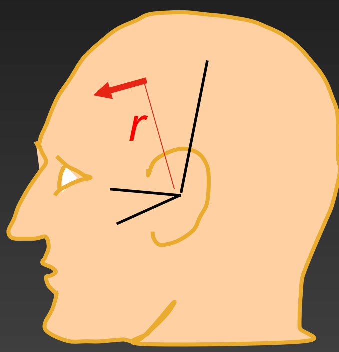
- Deviation from correct orientation can significantly attenuate output of beamformer (Hillebrand and Barnes, 2003)
- Requires realistic surface, accurate co-registration between MEG and MRI coordinate systems



Adaptive (Minimum-variance) Beamforming

Calculation of Spatial Filter:

For location r, define spatial filter as weight matrix, $\mathbf{W}(r)$

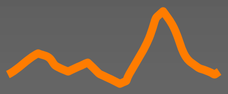


Filter output as function of time is measured data vector m(*t*) scaled by weights

$$\mathbf{S}(r,t) = \mathbf{W}(r)^{\mathrm{T}}\mathbf{m}(t)$$

Dimensions of $\mathbf{W}(r)$ = N source orientations x M channels

For scalar beamformer (source has single optimized orientation)

$$\mathbf{s}(r,t) = \mathbf{w}(r)^{\mathrm{T}}\mathbf{m}(t)$$ (*"virtual sensor"*) → 

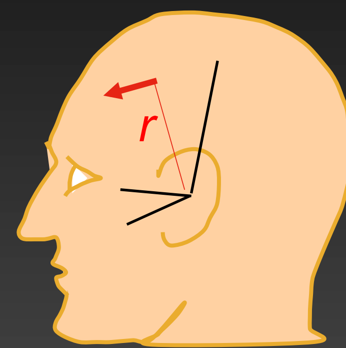
Adaptive (Minimum-variance) Beamforming

How do we obtain optimal weights $\mathrm{W}(r)$,
when number and location of brain sources are unknown?

Adaptive (Minimum-variance) Beamforming

Total source power emanating from location *r* over time period *T* is given by

$$P = \int_T \left\| \mathbf{w}(r)^{\mathrm{T}} \mathbf{m}(t) \right\|^2 dt$$



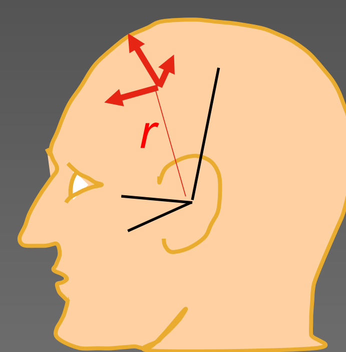
In matrix notation

$$P = \mathbf{w}(r)^{\mathrm{T}} \mathbf{C} \mathbf{w}(r)$$

where C = M channel x M sensor covariance matrix

For multi-dimensional weights, signal power is given by

$$P = tr\left\{ \mathbf{W}(r)^{\mathrm{T}} \mathbf{C} \mathbf{W}(r) \right\}$$



Adaptive (Minimum-variance) Beamforming

To obtain optimal weights, minimize total source power

$$\min_{\{W(r)\}} P = \mathbf{W}(r)^{\mathrm{T}} \mathbf{C} \mathbf{W}(r)$$

subject to constraint (retain unit gain for target forward model):

$$\mathbf{W}(r)^{\mathrm{T}} \mathbf{L}(r) = \mathbf{I}$$

where $\mathbf{L}(r)$ = forward solution for current dipole at location *r*

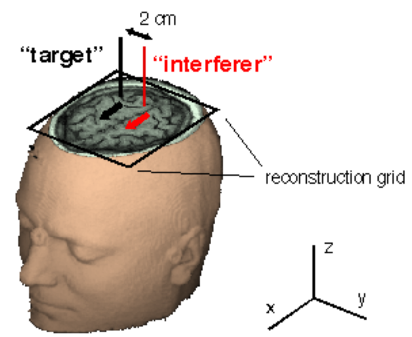
Solution for weights is given by,

$$\mathbf{W}(r) = \mathbf{C}^{-1} \mathbf{L}(r) \left[\mathbf{L}(r)^{T} \mathbf{C}^{-1} \mathbf{L}(r) \right]^{-1}$$

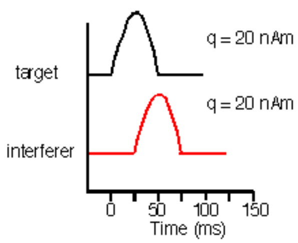
Spatial filtering methods – beamforming vs. SSP

(A)

Simulation (2 sources)



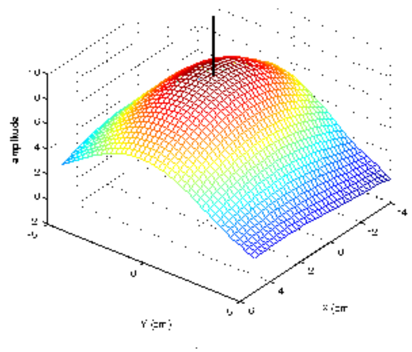
activation functions



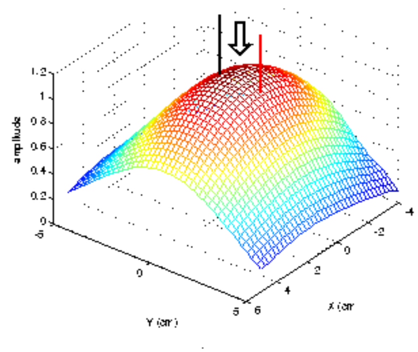
\+ 200 trials Gaussian noise
(rms noise = 10 ft / $Hz^{1/2}$)

SSP

target source only



target source + interferer



Adaptive (Minimum-variance) Beamforming

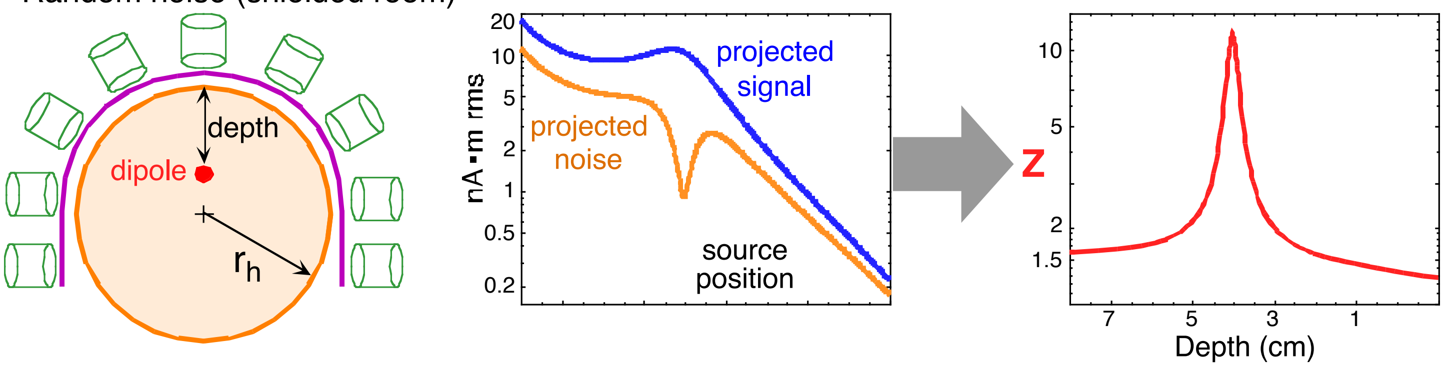
Problem:

Beamformer filter can only suppress noise sources that are correlated across sensors

Uncorrelated noise (e.g., system noise) will be amplified by weights non-linearly with increasing source depth.

Spatial filtering methods – noise based normalization

Simulated case,
r_h = 9 cm, q = 10 nA·m rms
Random noise (shielded room)



Projected signal $S^2 = W^TCW$

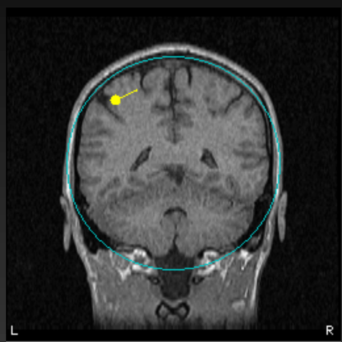
Projected noise $N^2 = W^T\Sigma W$, where Σ = diagonal noise matrix

Ratio = S^2 / N^2

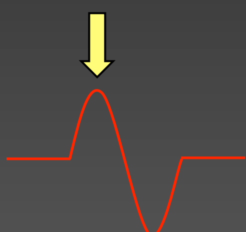
This ratio is also termed "pseudo-Z" (Robinson and Vrba, 1999) or "neural activity index" (Van Veen et al., 1997)

Figure courtesy of J. Vrba

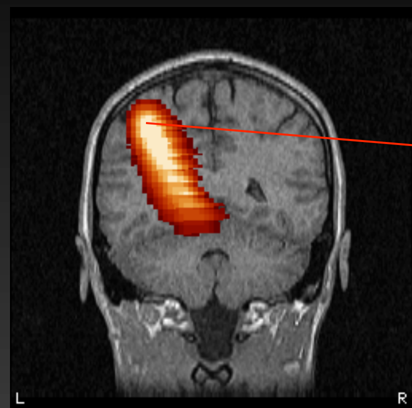
Spatial filtering methods – weight normalization



Source location

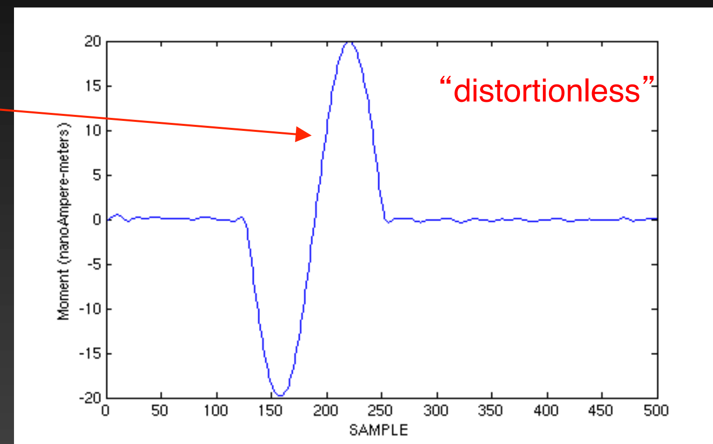


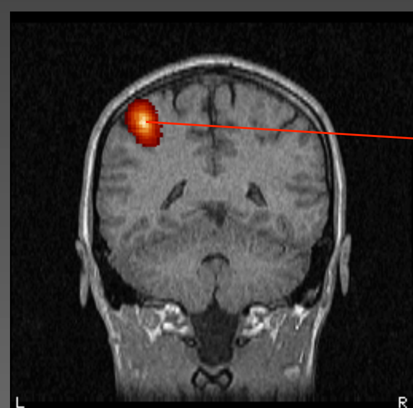
Source activity
(max = 20 nAm)



Non-normalized
(units = nA-m)

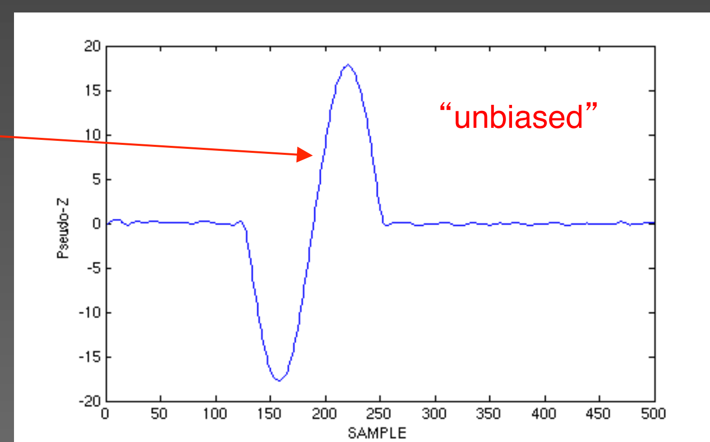
virtual sensor at peak (nA-m)





Normalized
(units = pseudo-Z)

virtual sensor at peak (pseudo-Z)

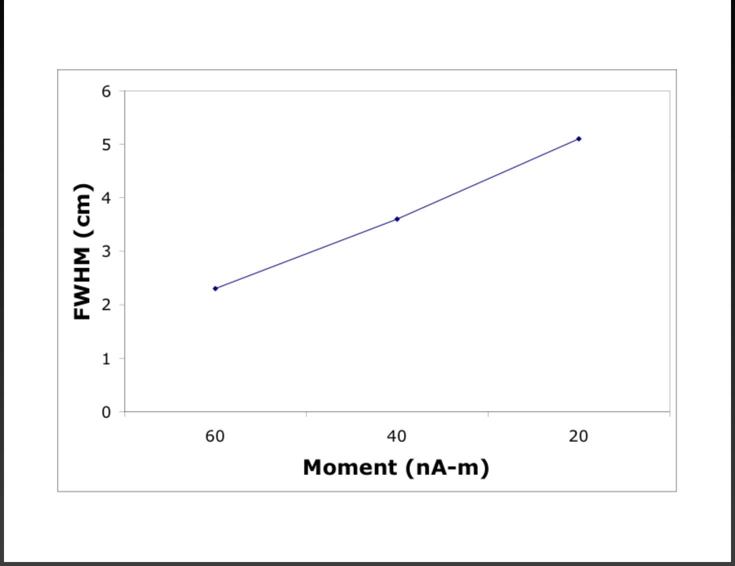


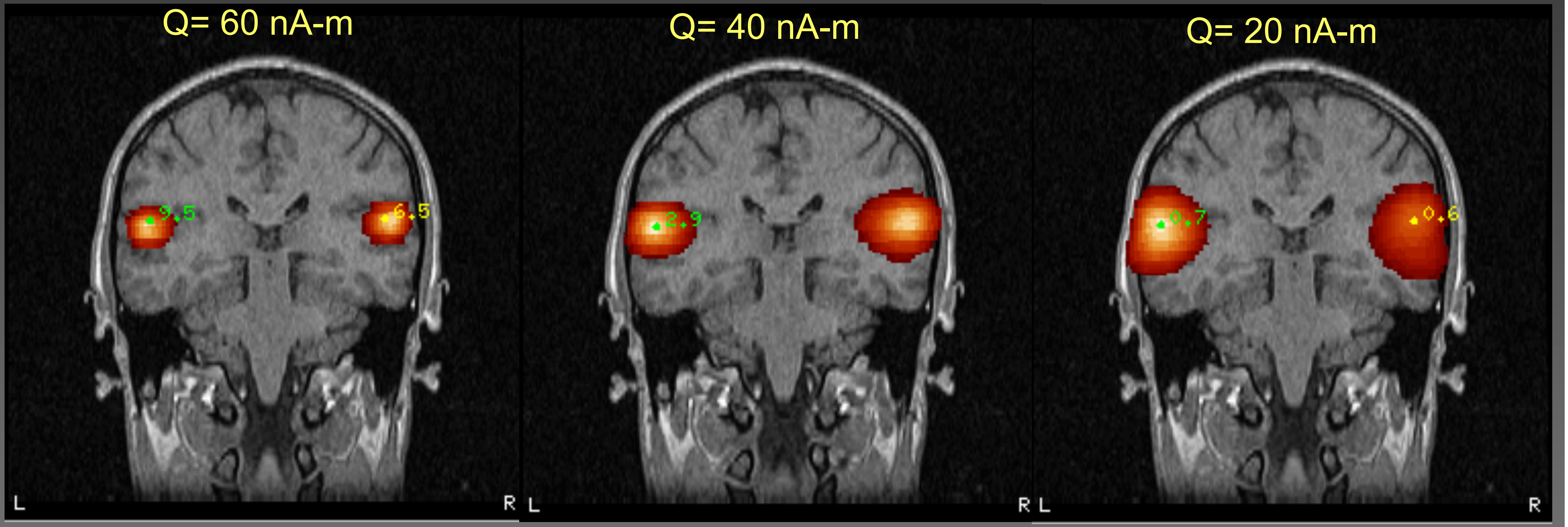
Greenblatt, Ossadtchi & Pflieger, Local linear estimators for the biomagnetic inverse problem. IEEE Trans Signal Proc., 2005

Effect of SNR on beamformer resolution

Simulated bilateral auditory cortex sources

X = 0.0 cm
Y = 5.5 and -5.5 cm
Z = 6.0 cm
+
Gaussian noise

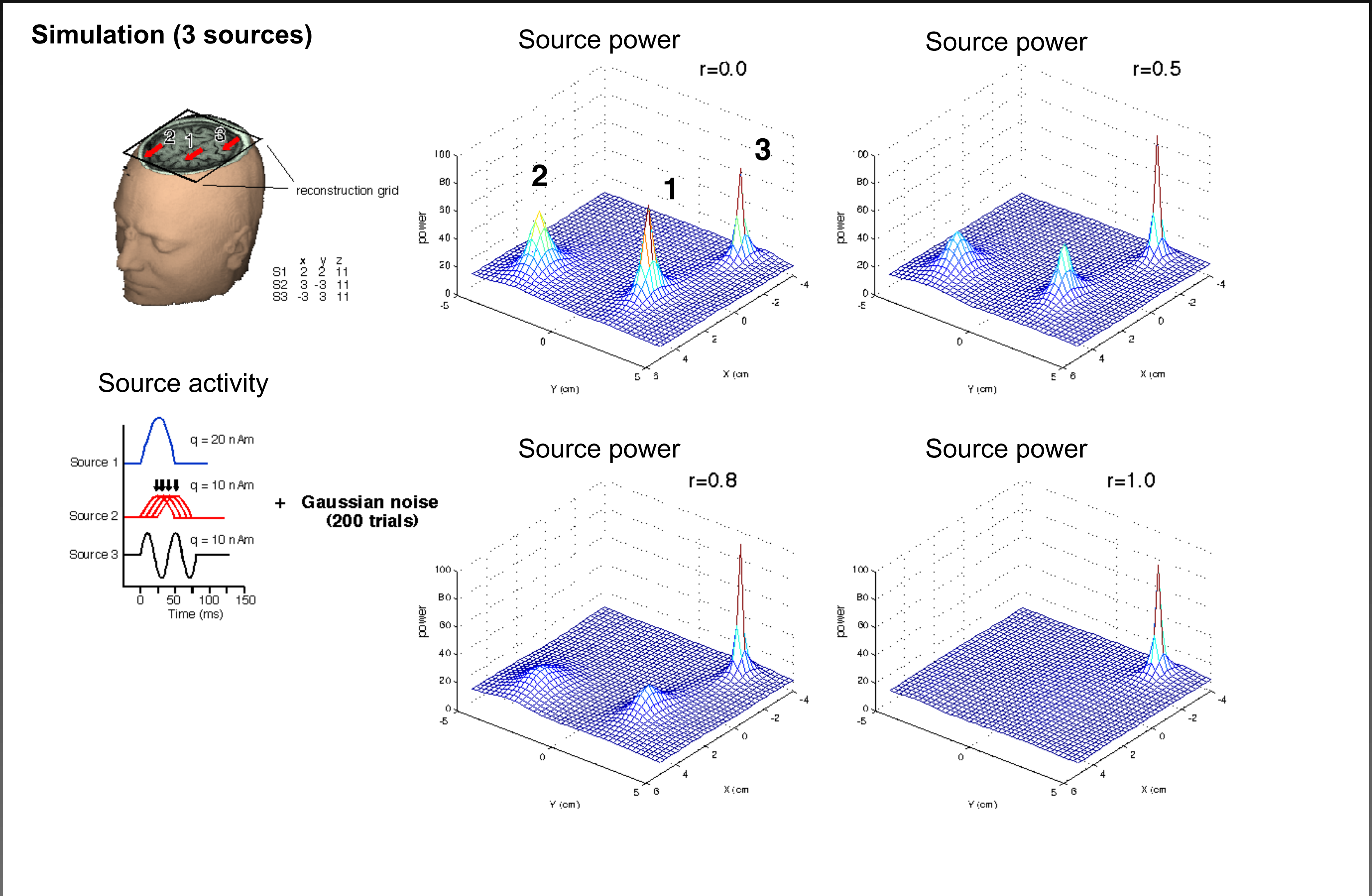




Applications of Beamformers in MEG

- Introduction to adaptive beamformers
- **Advantages and disadvantages of beamformers**
- Differential vs. event-related imaging
- Examples of clinical applications

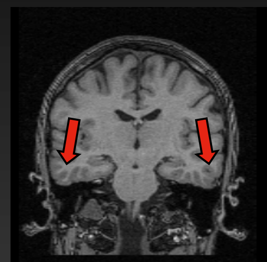
Spatial filtering methods – effects of source correlation



Spatial filtering methods – effects of source correlation

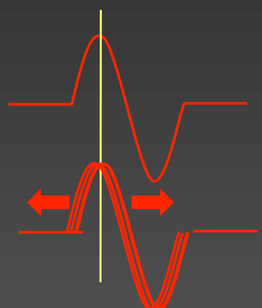
Simulation (auditory evoked fields)

Source 1 (0, 5.5, 6.0)
Source 2 (0, -5.5, 6.0)
Gaussian noise (10 - 20 fT / $Hz^{1/2}$)
150 trials

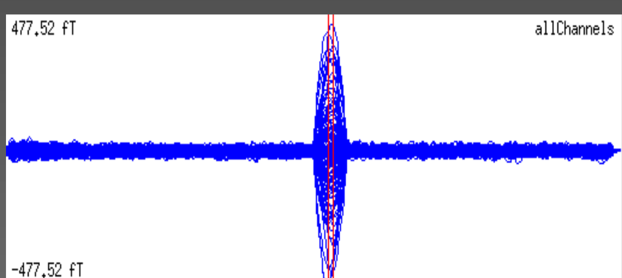


left

right

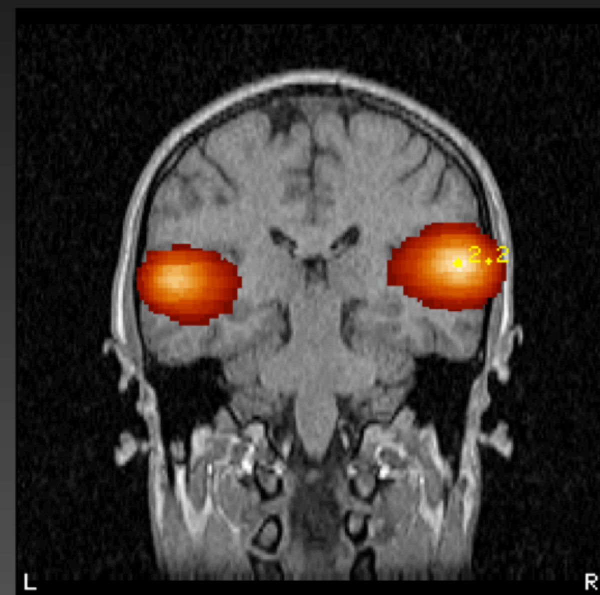


Right hemisphere source jittered trial-by-trial by 6 ms



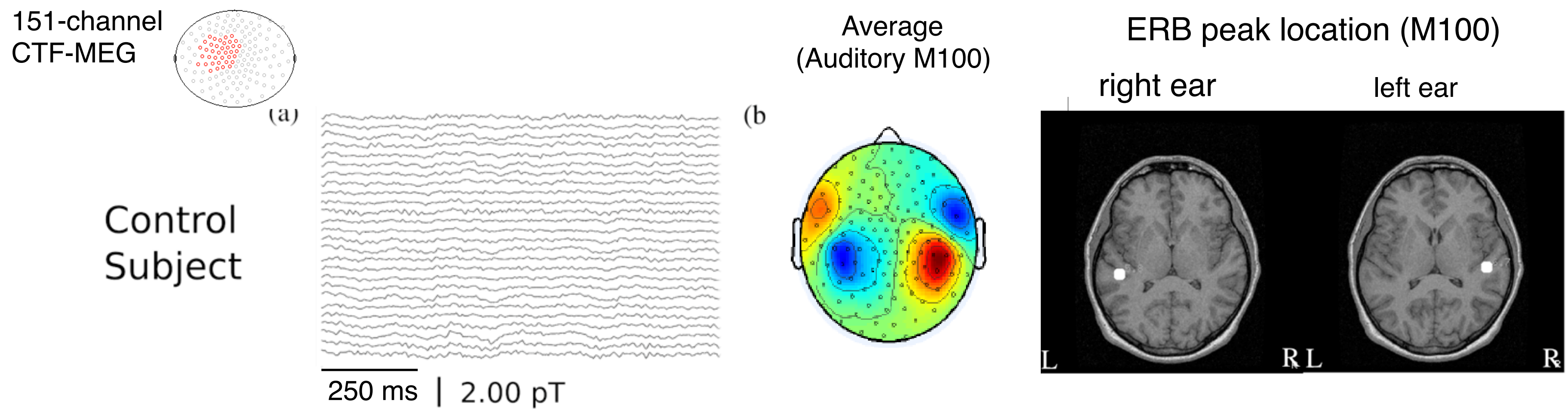
Average (all sensors)

Beamformer source reconstruction



Trial-by-trial latency jitter of 6 ms reduces effect of correlation

ERB localization with braces motion artifact

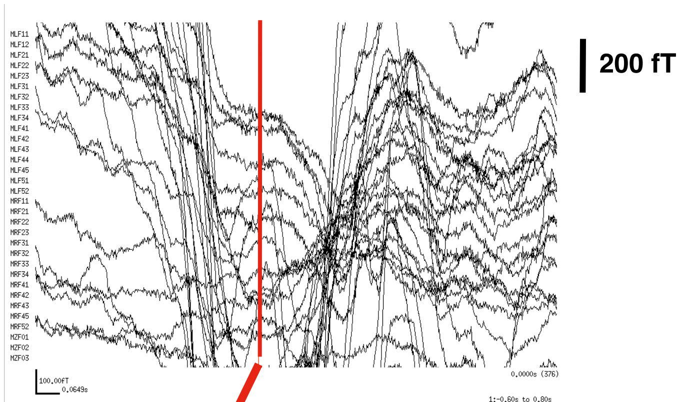


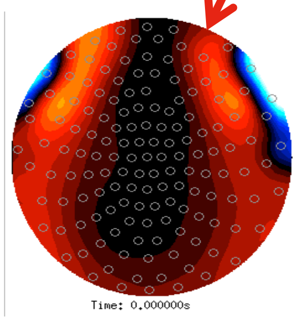
Cheyne, Bostan, Gaetz & Pang (2007)

ERB method suppresses ferromagnetic artifacts

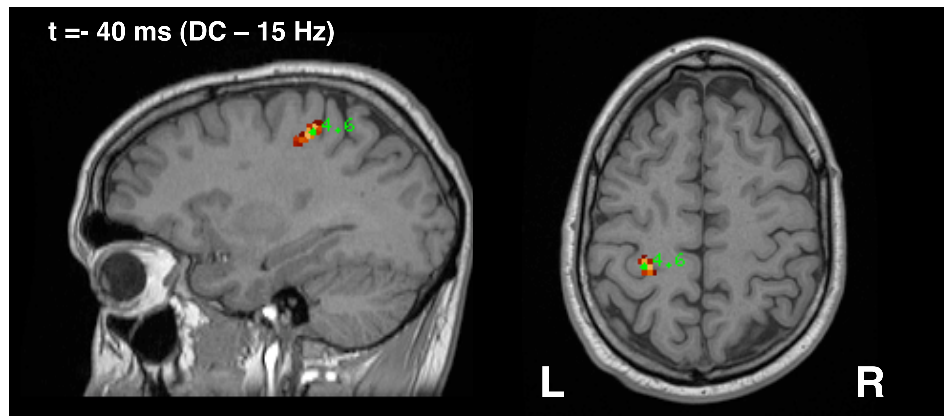
Motor Field (MF) localization in subject with metal retainer

Average (frontal sensors)





ERB source image (2 mm)



Right index finger movement

Applications of Beamformers in MEG

- Introduction to adaptive beamformers
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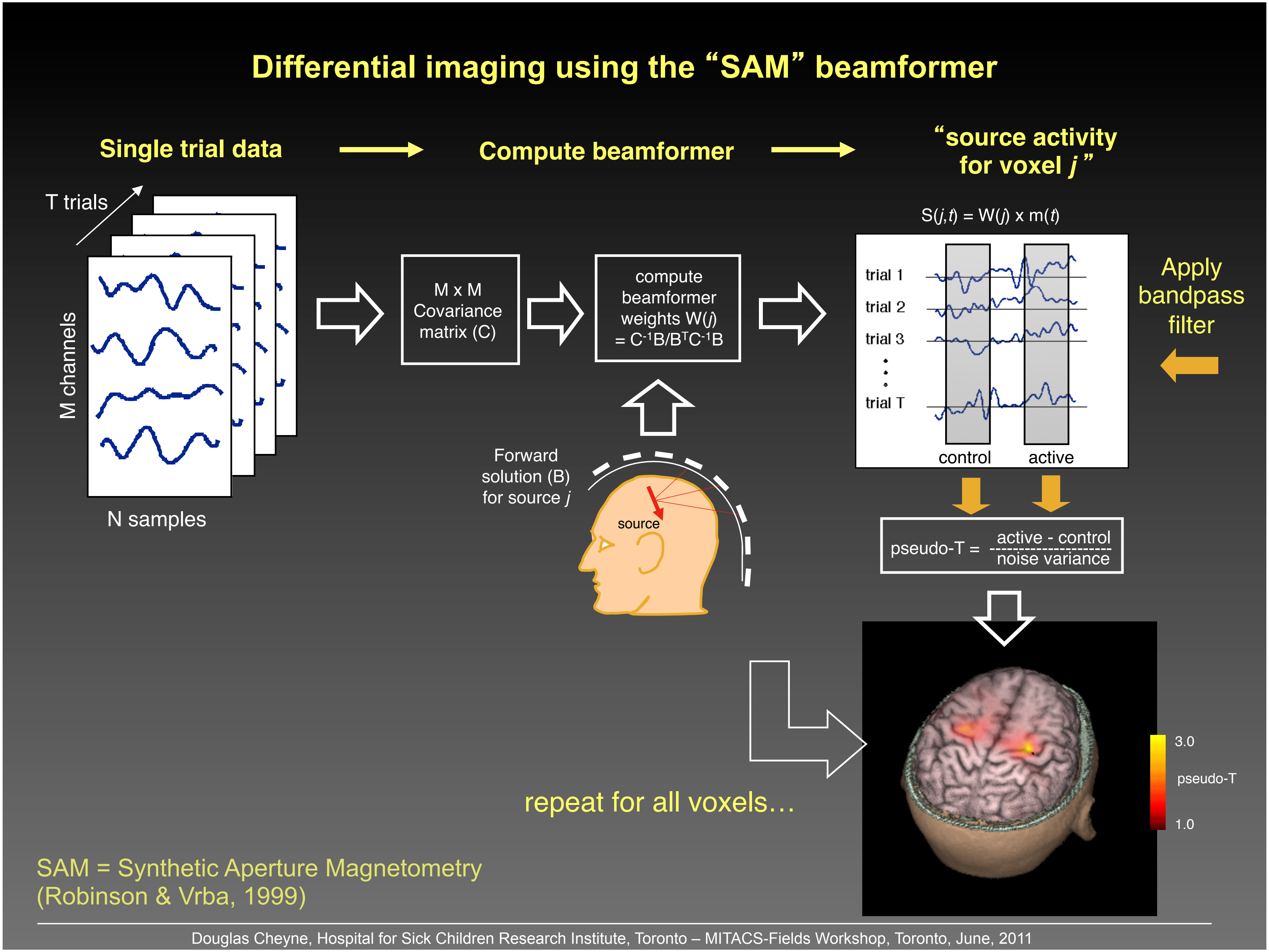
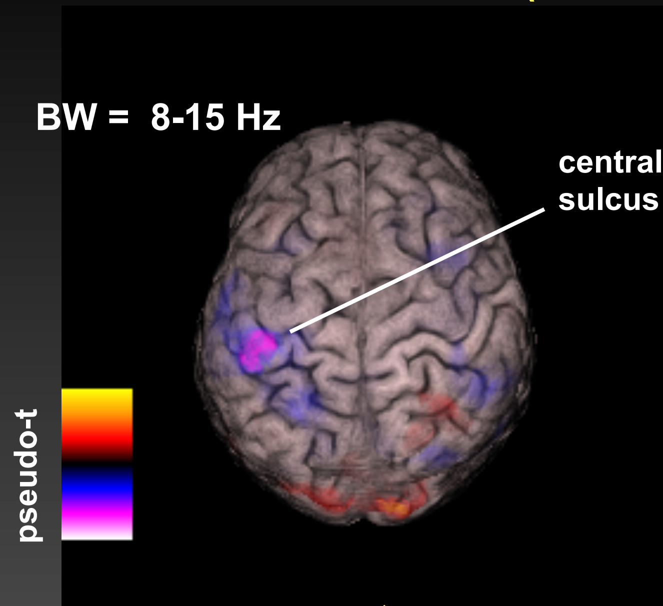
- **Differential vs. event-related imaging**
- Applications of beamformers in epilepsy

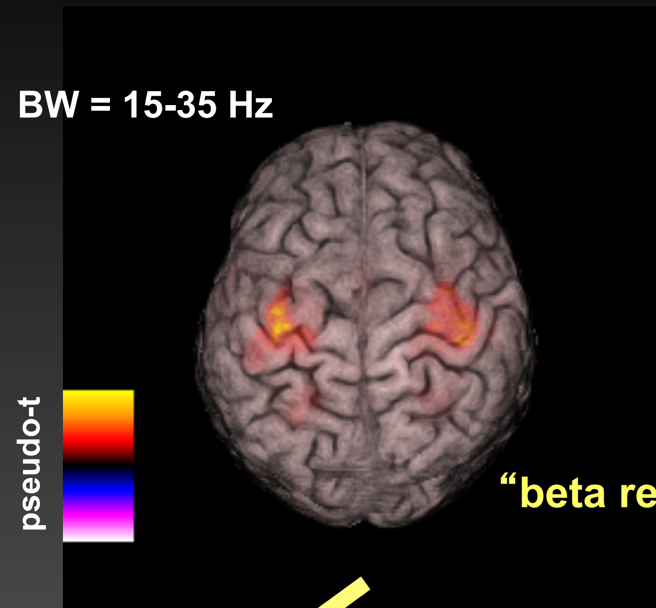

Differential imaging using the "SAM" beamformer
Single trial data
Compute beamformer
"source activity for voxel j"
T trials
M channels
N samples
M x M Covariance matrix (C)
compute beamformer weights W(j) = C-1B/BTC-1B
Forward solution (B) for source j
source
S(j,t) = W(j) x m(t)
trial 1
trial 2
trial 3
trial T
control
active
Apply bandpass filter
pseudo-T = active - control / noise variance
3.0
pseudo-T
1.0
repeat for all voxels…
SAM = Synthetic Aperture Magnetometry
(Robinson & Vrba, 1999)
Douglas Cheyne, Hospital for Sick Children Research Institute, Toronto – MITACS-Fields Workshop, Toronto, June, 2011

Movement-related mu and beta oscillations

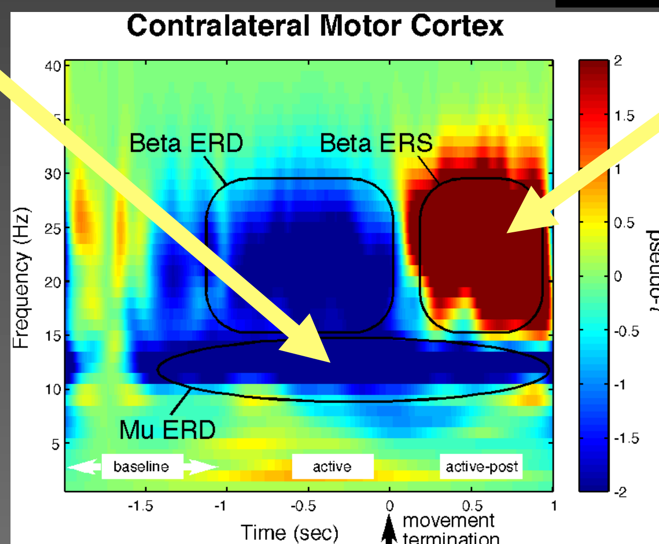
Pre-movement mu (-0.5 to 0 s)



Post-movement beta (0.5 to 1 s)



"beta rebound"

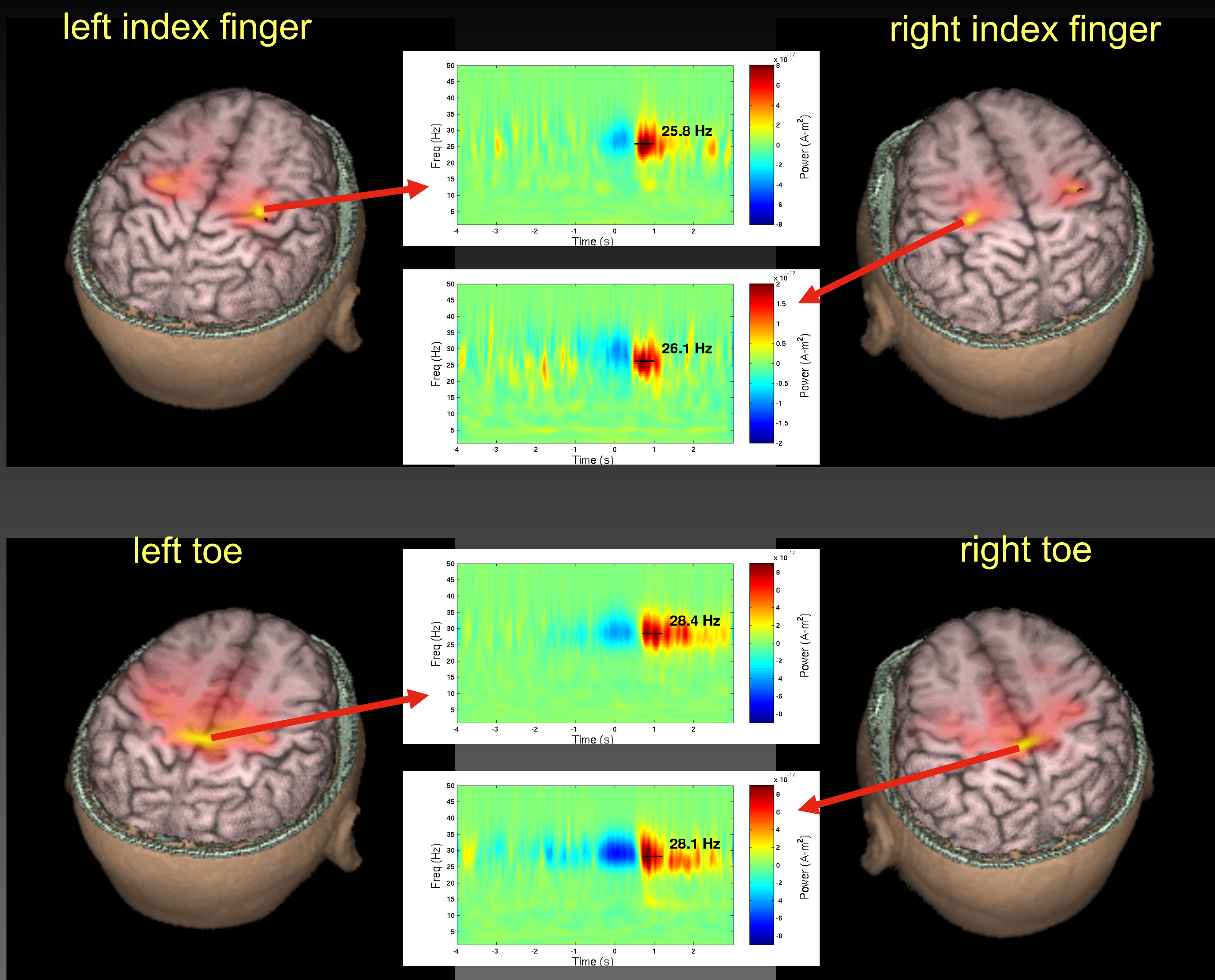


Right index finger movement

Source activity in left sensorimotor cortex

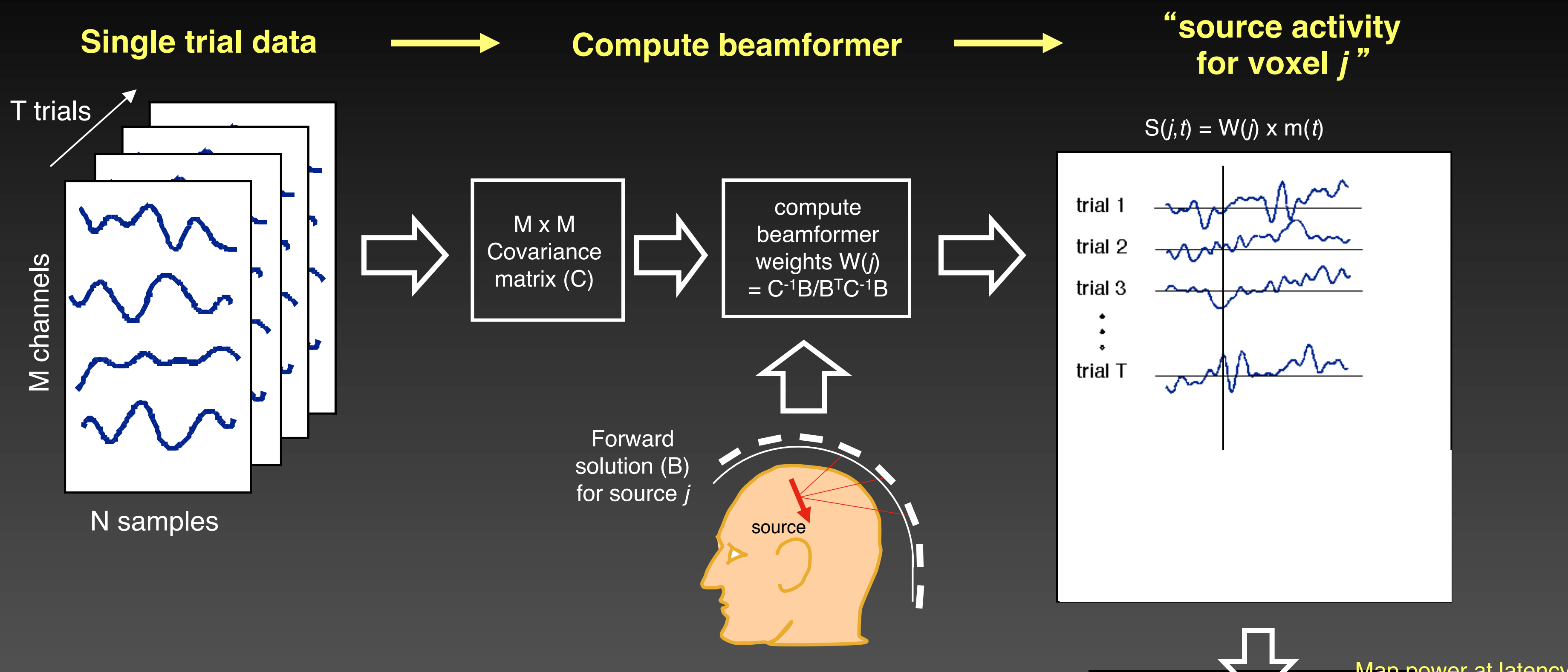
Jurkiewicz, Gaetz, Bostan & Cheyne, NeuroImage, 2006

Beta rebound somatotopy

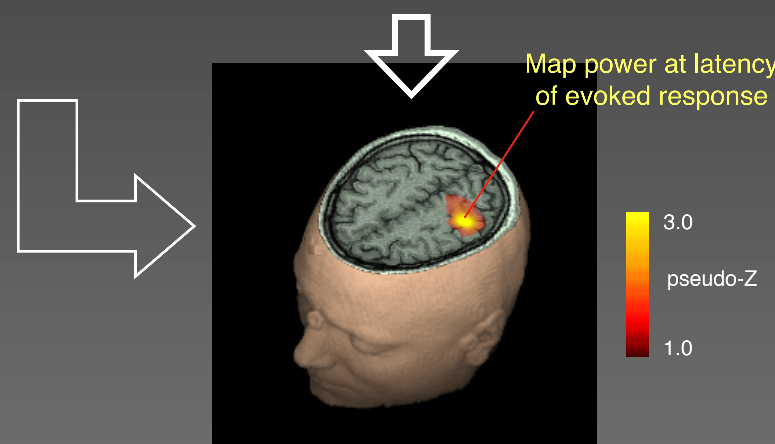


Differential SAM images - rebound period (0.5 - 1 s) minus baseline

Event-related (spatiotemporal) beamformer

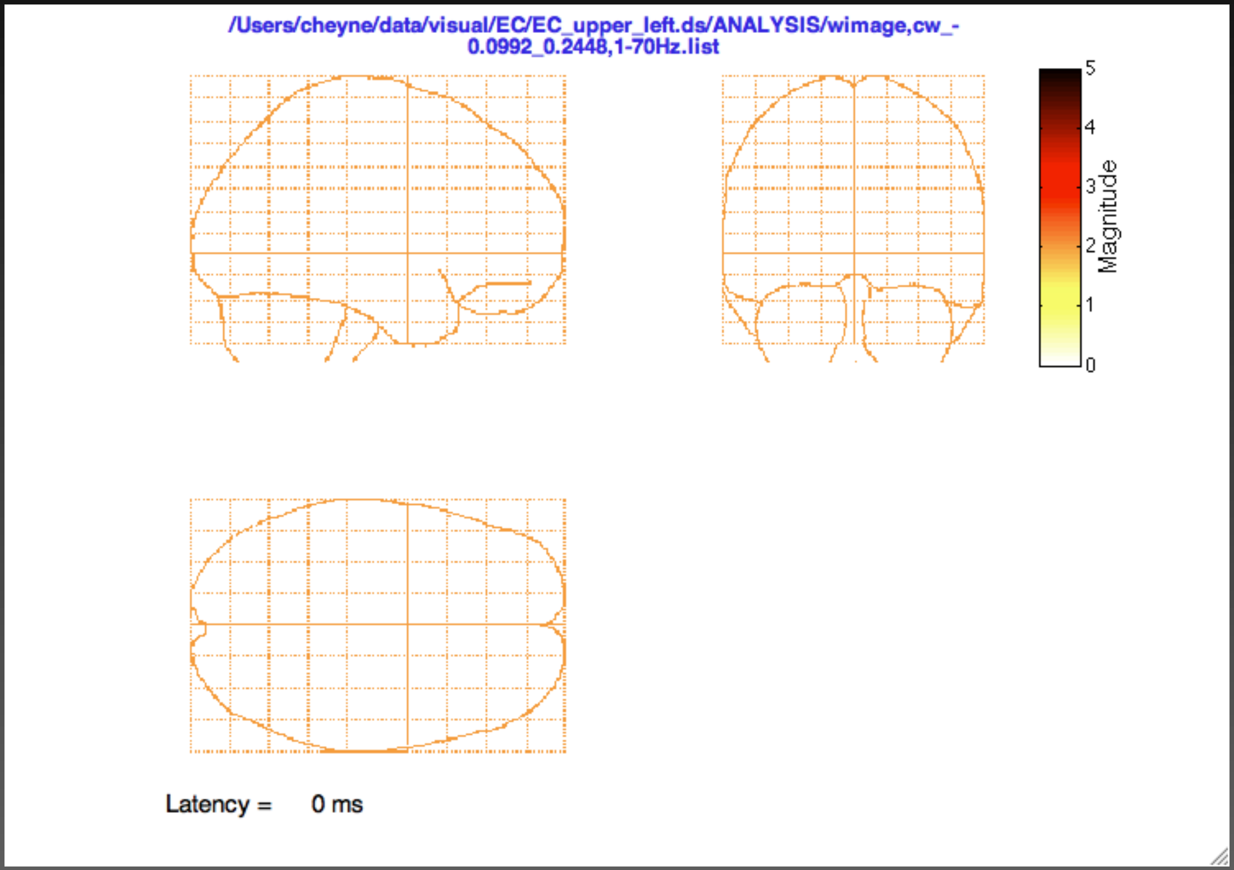


repeat for all voxels…



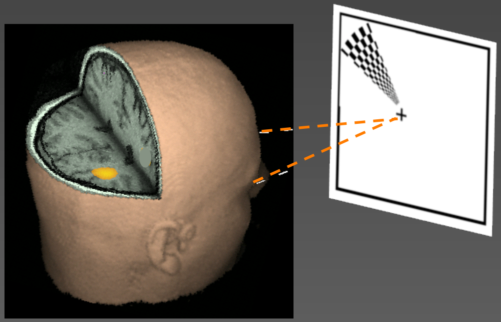
- Spatiotemporal beamformer (Sekihara et al., 2002)
- Event-related beamformer (Cheyne et al.,2004, 2006)
- SAMerf (Robinson, 2004)

Spatiotemporal beamformer analysis of evoked brain activity



Visual evoked response (upper left quadrant)

Movie of source images computed every 1 ms from 0 to 240 ms



images created with BrainWave toolbox (Cheyne and vanLieshout, 2010)

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- **Examples of clinical applications**

MEG at SickKids

11 months

4 year old

18 year old

Children undergoing clinical MEG at Sickkids (2000 – May, 2009)

< 4 years olds (n = 59)
4-8 years olds (n = 165)
9-18 years old (n = 421)
adults (19+) (n = 91)
Total = 736

MEG at SickKids

Clinical applications of MEG at SickKids:

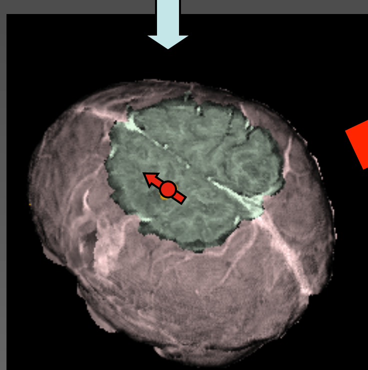
- Surgical planning (epilepsy)
- Presurgical mapping of sensory and motor cortex (e.g., tumour resection)
- Language lateralization (substitute for Wada test)

Presurgical Functional Mapping

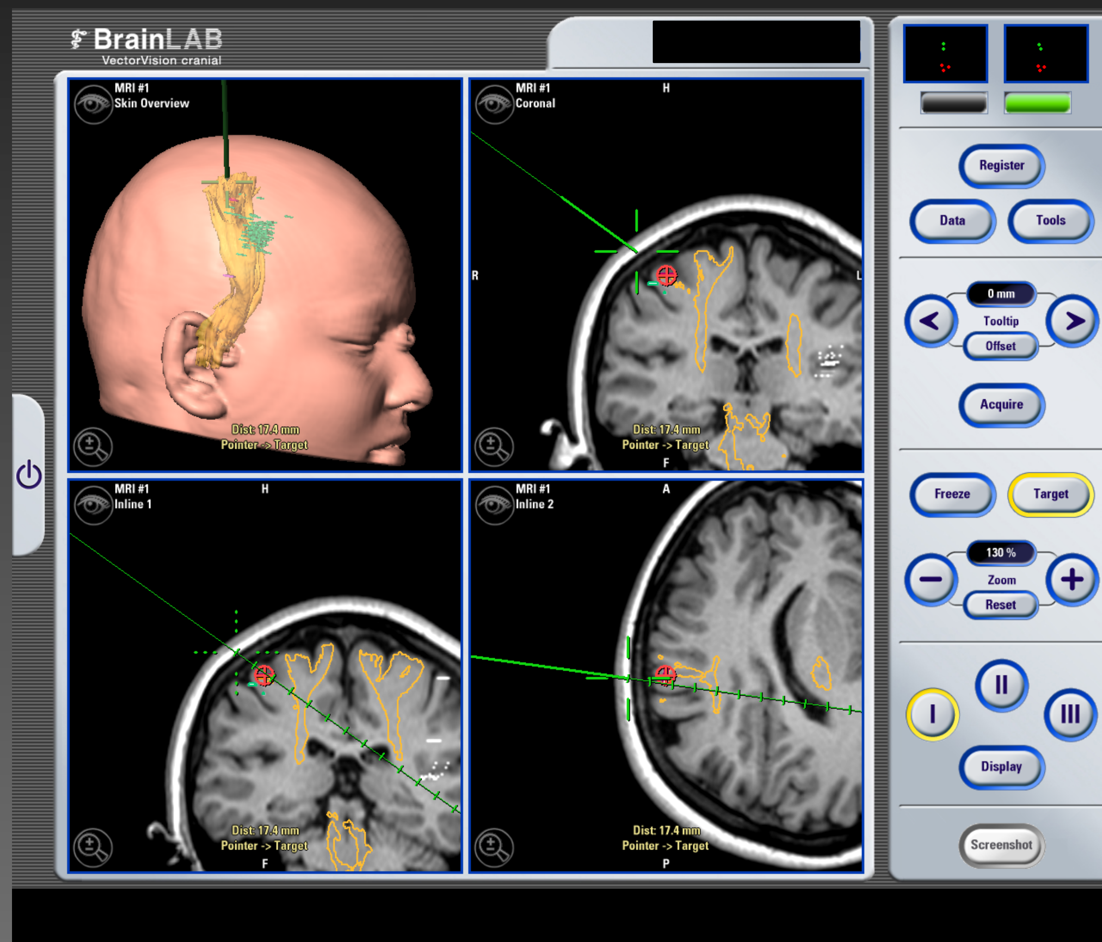
Evoked Field

Dipole Fit

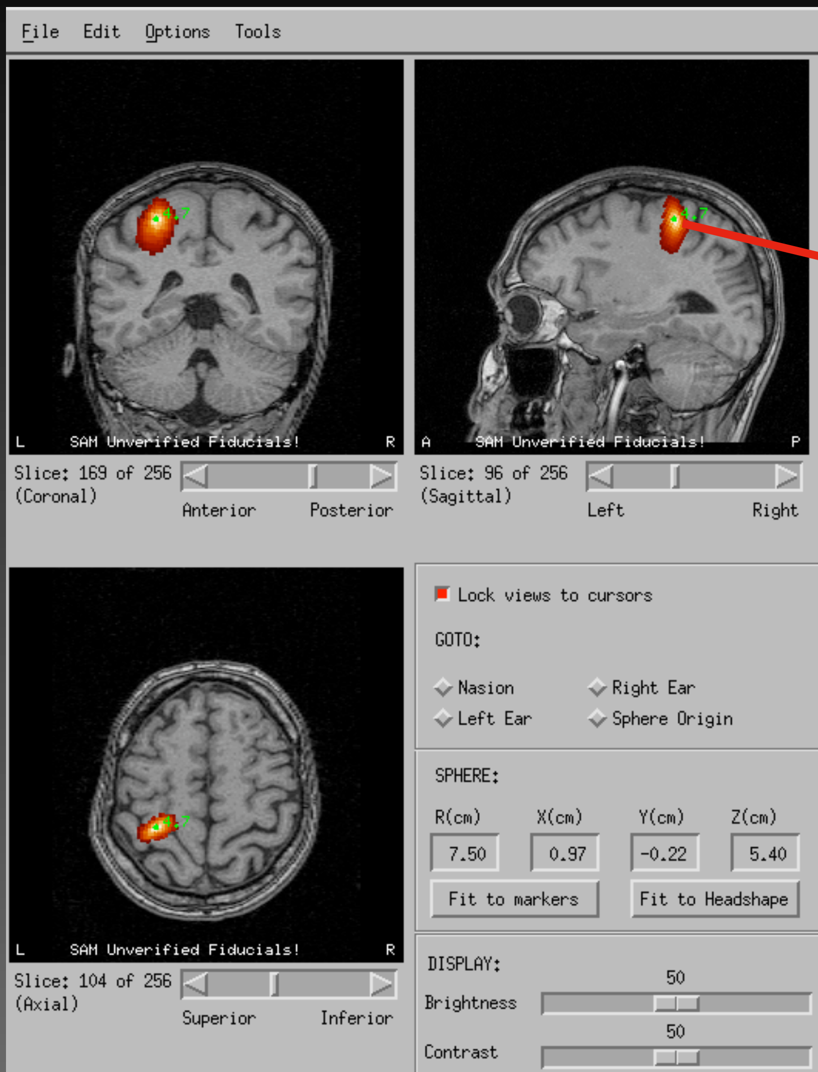
MEG-MRI coreg

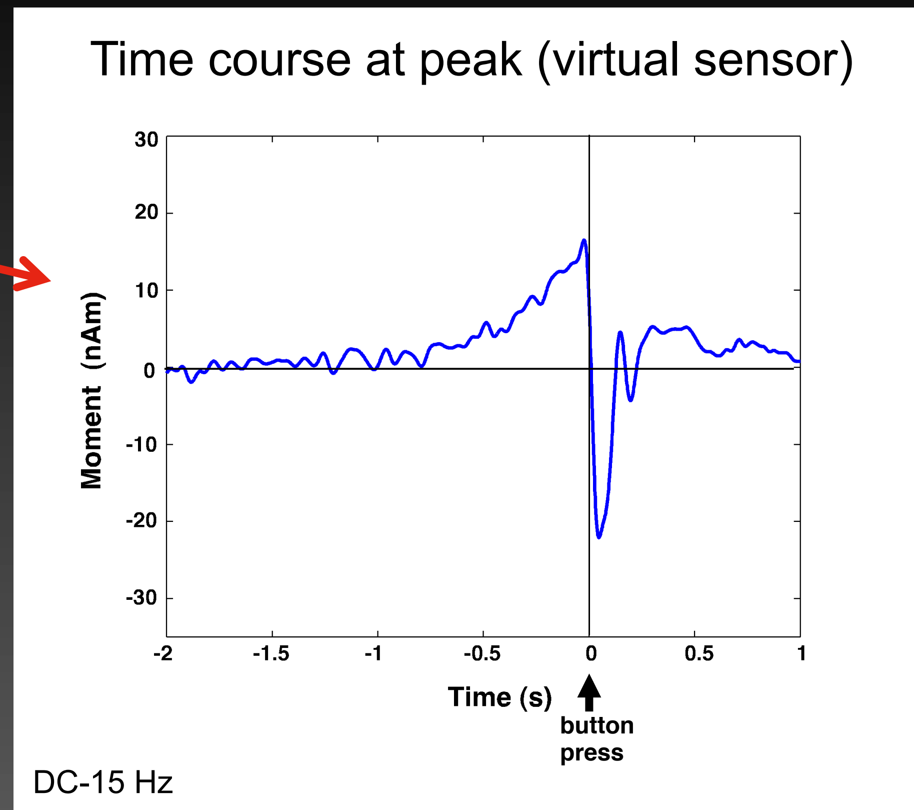


Neuronavigation



Beamformer localization of premovement motor field (MF)



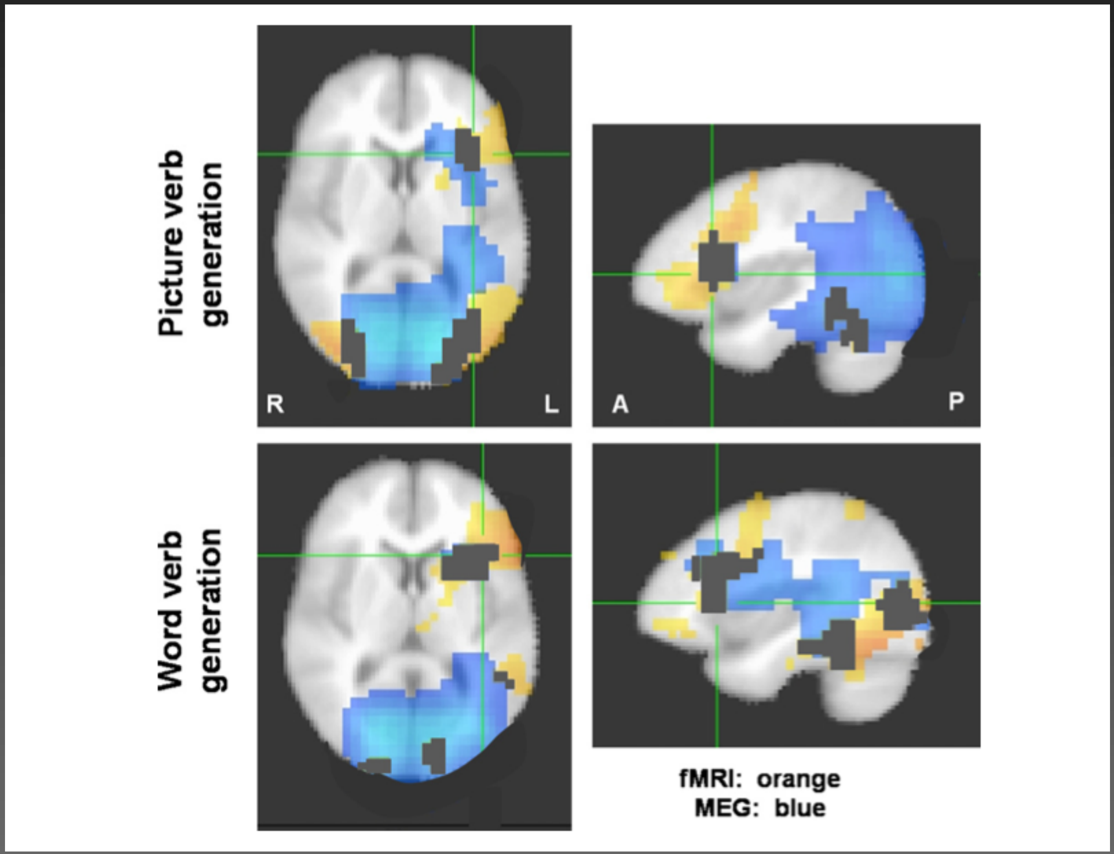


Self-paced right index finger movement
Recording time ≈ 10 min (100-130 movements)

ERB image in MRIViewer (t = -40 ms, threshold = FWHM)

Language lateralization using differential beamformer

Concordance between fMRI and MEG beamformer lateralization of language function (covert picture and word verb generation task)

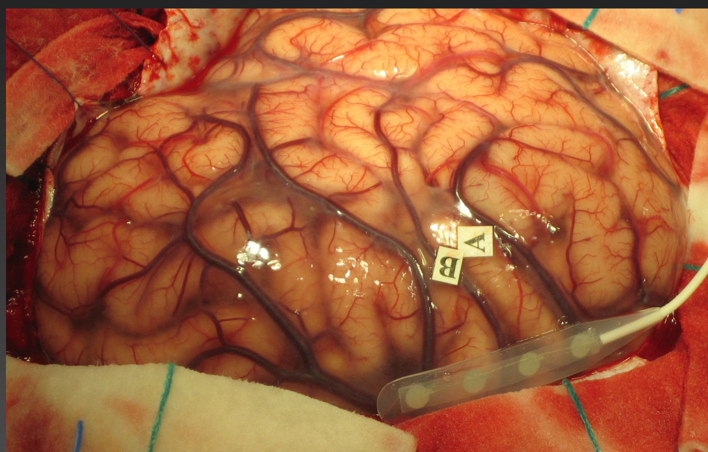


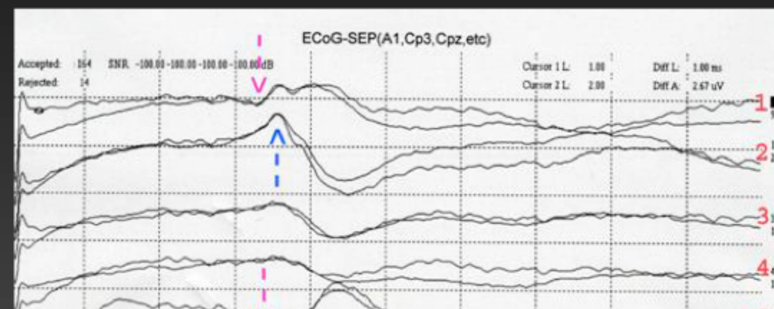
MEG = suppression of source power in beta band localized with SAM beamformer

From Pang, Wang, Malone, Kadis and Donner (2011)

Presurgical Motor Mapping using Beamformers

Interoperative confirmation using cortical stimulation





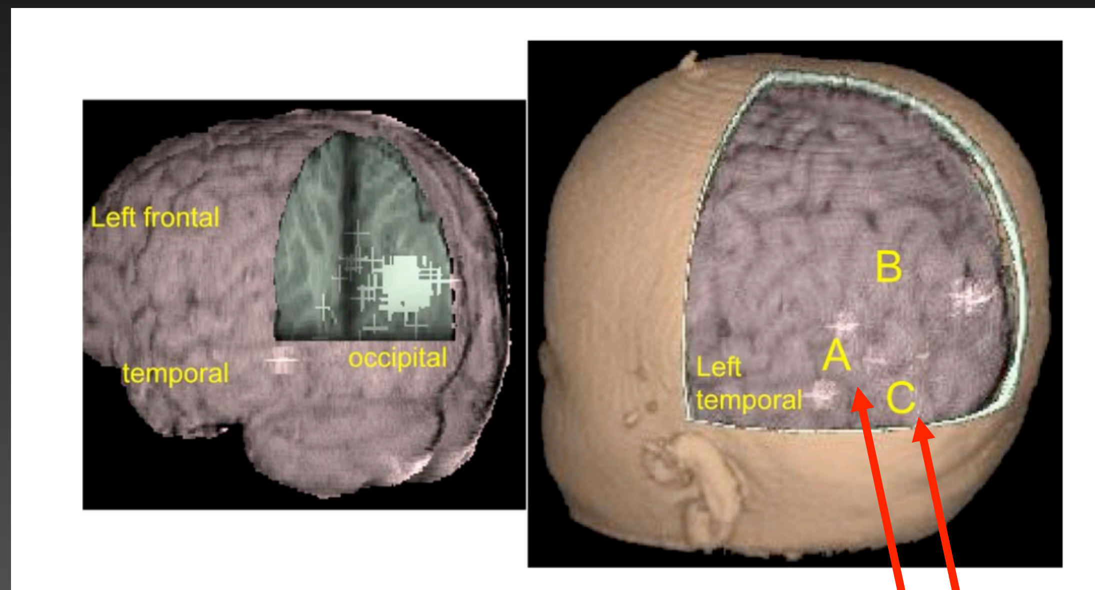
A, MEG SEF
B, MEG motor

- Pang, E.M., Drake, JM., Otsubo H., Martineau A., Strantzas S., Cheyne D., Gaetz W. (2008) Interoperative confirmation of hand motor area identified preoperatively by magnetoencephalography: A clinical case study. Pediatric Neurosurgery 44:313-317
- Gaetz W., Cheyne D., Drake J., Rutka J., Benifla M., Strantzas S., Widjaja E., Holowka S., Otsubo H., and Pang E.W. (2009) Pre-surgical localization of primary motor cortex in paediatric patients with brain lesions using spatially filtered magnetoencephalography. Neurosurgery 64 (3): 177-186.

Applications of beamformers in epilepsy

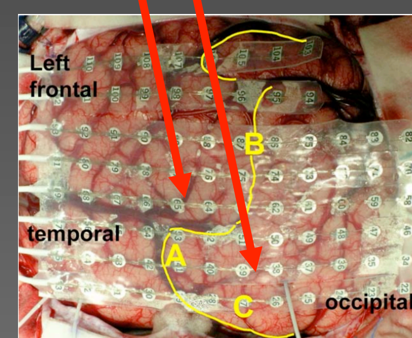
Modeling interictal spikes as single dipoles (dipole clusters)

Co-registration of dipole cluster with patient's MRI



Limitations of dipole fitting approach for epilepsy:

- **Low SNR due to lack of signal averaging**
- **High-amplitude interictal spikes involve large areas of activation**



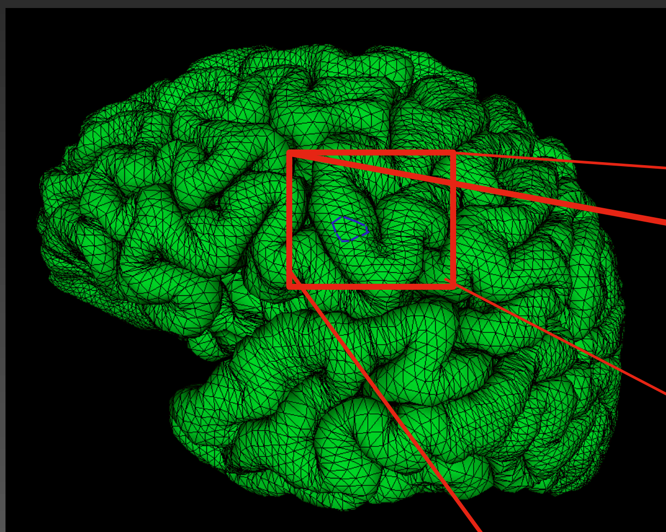
Data courtesy of H. Otsubo, Hospital for Sick Children

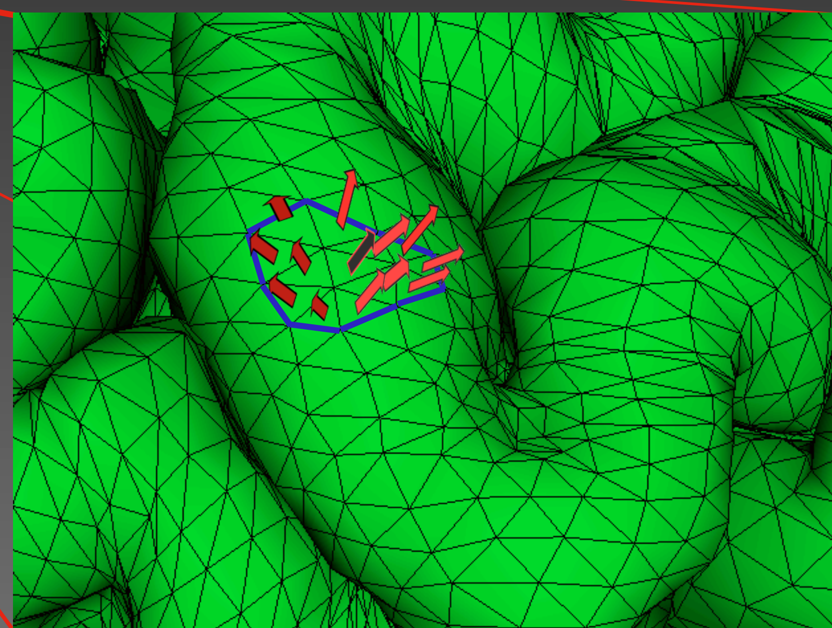
Applications of beamformers in epilepsy

Can beamformers image extended sources?

Extended (dipole patch) source

- **triangulated mesh (≈ 80,000 triangles / hemisphere)***
- **patch growing using seed location and neighboring triangles**
- **uniform current density (0.5 nAm/mm^2)**



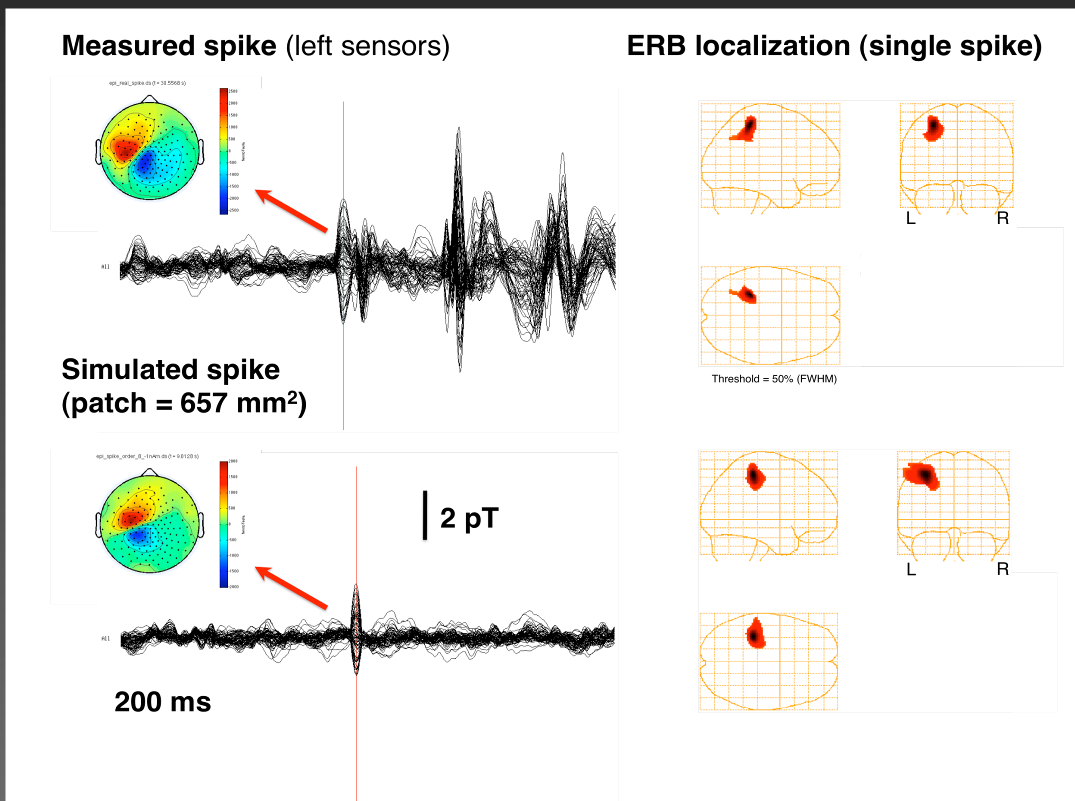


*cortical segmentation courtesy of Dr. Jason Lerch
Mouse Imaging Centre, Toronto Centre for PhenoGenomics

Applications of beamformers in epilepsy

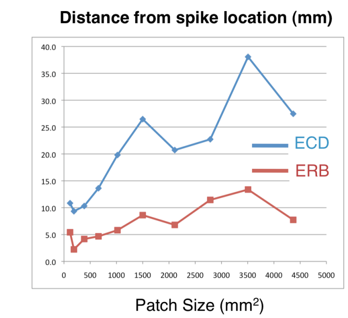
Simulated interictal spike

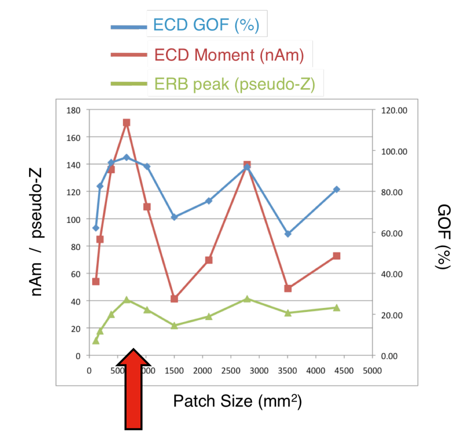
- data from 12 year-old female patient with right-sided seizures
- dipole coordinates of interictal dipole fit used as seed for patch
- 1.0 nAm/mm^2 current density
- added to spontaneous activity with no spiking activity
- single 14 s duration trial (BW = 1 – 70 Hz)



Patch simulation parameters

Neighborhood order	# triangles	Total area (mm^2)	Total moment (nAm)
3	73	115	115.3
4	121	189	188.9
6	253	386	385.7
8	433	657	657.0
10	657	1019	1018.8
12	921	1500	1499.5
14	1225	2110	2110.2
16	1569	2787	2786.9
18	1953	3506	3506.3
20	2377	4367	4367.3





Model optimal for approx. 6 cm^2 patch

Cheyne, Lerch, Mohamed, Ferrari, Lalancette, Pang and Otsubo, (Biomag, 2010)

Acknowledgments:

Cheyne Lab:

Dr. Paul Ferrari
Dr. Natasha Alves
Ze-chuan He
Marc Lalancette
Natascha van Lieshout

Department of Diagnostic Imaging and Division of Neurology (SickKids):

Dr. Liz Pang
Dr. Hiroshi Otsubo
Dr. Ismail Mohamed

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